

Neutrinos in Cosmology

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Abstract

Cosmological implications of neutrinos are reviewed. The subjects considered involve: (a) bounds on neutrino mass from the observational limits on the universe age and the Hubble constant both in cosmology with and without cosmological constant; (b) distortion of spectrum of cosmic neutrinos; (c) bounds on neutrino mass from primordial nucleosynthesis; (d) lepton asymmetry of the universe; (e) neutrino oscillations and possible new sterile neutrinos; (f) neutrino role in large scale structure formation.

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1 Introduction.

There are several important subjects in cosmology where neutrinos play (or may play) a significant role. Among them are primordial nucleosynthesis, dark matter, and the large scale structure formation. In the last two cases neutrinos are important only if they are massive. Unfortunately there is no direct experimental evidence for nonzero m_ν , though the accuracy of experiments is rather loose especially for ν_μ and ν_τ :

$$m_{\nu_e} < 5 \text{ eV} [1] \tag{1}$$

$$m_{\nu_\mu} < 160 \text{ keV} [2] \tag{2}$$

$$m_{\nu_\tau} < 24 \text{ MeV} [3] \tag{3}$$

Though direct measurement give only upper bounds for m_ν there are accumulated indirect data on anomalous neutrino behaviour which can be nicely explained by neutrino oscillations. If this is the case, then neutrino mass should be nonvanishing. (Inverse is not true, nonzero masses of different neutrino flavors do not necessarily imply oscillations though the absence of oscillations in this case would be very unnatural.)

Theory neither demands nor forbids nonzero neutrino mass. In all the known cases of massless particles there is a theoretical principle which not only explains the vanishing of the mass and also protects its zero value against radiative corrections. For example vanishing masses of photon and graviton are ensured respectively by gauge invariance in QCD or by coordinate covariance in general relativity. No similar principle is known for neutrinos. So if "anything which is not forbidden is permitted", neutrinos should be massive. One may hope that mass spectrum of neutrinos is related to a new physics at high energy scale beyond that of electroweak interactions. Since this scale is unknown, theory does not say anything about possible values of neutrino masses and one is free to speculate about them in the limits permitted by experiment, cosmology, and astrophysics. Except for restrictions on

neutrino mass cosmology permits to put bounds on neutrino oscillation parameters, magnetic moments, and decay properties.

2 Relic Neutrinos and Cosmological Bounds on Their Mass.

Neutrinos are the most abundant particles in the Universe after photons of cosmic microwave background radiation. Their number density is determined by thermal equilibrium which existed in the early universe and is given by

$$n_{\nu_j} = n_{\bar{\nu}_j} = (3/22)n_\gamma \quad (4)$$

where $j = e, \mu, \tau$ and $n_\gamma = 400(T_\gamma/2.7 K)^3 cm^{-3}$.

This result is valid if the following conditions are fulfilled:

1. Thermal equilibrium of neutrinos with the primeval electromagnetic plasma at temperatures above 3 MeV. This is known to be true and gives $n_\nu/n_\gamma = 3/8$.
2. Adiabatic heating of photons by e^+e^- -annihilation which increases the photon number density so that the above ratio goes down to $n_\nu/n_\gamma = 3/22$.
3. No other sources producing additional photons below neutrino decoupling (at $T = 3$ MeV). At sufficiently small temperatures, $T < 10$ keV, possible existence of such sources is strongly constrained by the accurate Planck spectrum of cosmic microwave radiation.
4. No new interactions of neutrinos. Their frozen abundance is determined by the usual weak interaction cross-section. If for example neutrinos possess Yukawa interaction with massless Goldstone boson (Majoron) with sufficiently large coupling constant g , their relative number density could be as small as $r_\nu \equiv n_\nu/n_\gamma \approx m_\nu/(g^4 m_{Pl})$ where

$m_{Pl} = 1.221 \cdot 10^{19}$ GeV is the Planck mass. Correspondingly the limit obtained below for m_ν would be weaker.

5. Relic neutrinos are 100% left-handed. If they have Dirac mass and participate in normal weak interactions only, this assumption is true roughly speaking with the accuracy $(m_\nu/MeV)^2$. For Majorana mass no additional states appear for any mass value.
6. Neutrino stability. Neutrino life-time should be bigger than the universe age, $t_U \approx 10^{10}$ years. Otherwise their number density at the present day would be smaller or even negligible. Still the influence of the decay products on the universe expansion rate permits to put some bounds on the mass/life-time even if the decay goes into invisible particles.
7. Vanishing chemical potential of neutrinos. This ensures equality $n_\nu = n_{\bar{\nu}}$. Normally leptonic chemical potentials are of the same order of magnitude as the baryonic one, which is known to be very small from the baryon asymmetry of the universe. Still strictly speaking a large lepton asymmetry is not forbidden and in this case the limit on the mass would be stronger. We return to the case of large neutrino chemical potentials in connection with primordial nucleosynthesis.

Energy density in the universe is characterized by the cosmological parameter $\Omega = \rho/\rho_c$ where $\rho_c = 3H^2 m_{Pl}^2/8\pi$ and H is the Hubble constant which is parametrized as $H = 100h_{100} km/sec/mpc$. Since the energy density of neutrinos (and antineutrinos) is smaller than the total energy density of matter we can write the upper bound on their mass (Gerstein-Zeldovich limit)[4] as:

$$\sum_j m_{\nu_j} < \Omega_m \rho_c / (n_\nu + n_{\bar{\nu}}) = 94 h_{100}^2 \Omega_m eV \quad (5)$$

Here Ω_m corresponds to energy density of matter in contrast to vacuum energy density (or cosmological constant). Since Ω is not a well known quantity it could be more restrictive

to express the bound on m_ν through the lower limit on the universe age and the Hubble parameter. The universe age is given by

$$t_U = \frac{1}{H} \int_0^1 \frac{dx}{(1 - \Omega_{tot} + \Omega_m/x + \Omega_r/x^2 + \Omega_v x^2)^{1/2}} \quad (6)$$

where Ω_m , Ω_r , and Ω_v are the present-day fractions of cosmological energy density of nonrelativistic matter, relativistic matter, and vacuum (cosmological constant); $\Omega_{tot} = \Omega_m + \Omega_r + \Omega_v$. In spatially flat universe, as advocated by inflationary scenario, $\Omega_{tot} = 1$. It is usually assumed that $\Omega_r \ll \Omega_m$ because relativistic energy density decreases faster in the course of expansion than the nonrelativistic one. It may be not so if there are late-decaying particle producing relativistic decay products at contemporary epoch. It is also assumed that $\Omega_v = 0$ (vanishing cosmological constant). This assumption has no theoretical justification, moreover any reasonable theoretical estimate gives the value of vacuum energy density 50-100 orders of magnitude bigger than the observational limit[5]. So having something so small, because of unknown mechanism, one assumes that this quantity is exactly zero. The recent conflict between a large universe age and a high value of the Hubble constant indicates that cosmological constant and correspondingly Ω_v might be nonzero. The universe age is determined from the ages of old globular clusters and the relative abundances of long-lived radionuclides and is found to be in the range $t_U = 12 - 15$ Gyr. Recently even a larger value, $t_U = 17$ Gyr, was advocated (for the review see [6]). The Hubble parameter is probably somewhere between $0.5 < h_{100} < 1$. The new data has tendency to higher values, $h_{100} = 0.7 - 0.8$ [7] but is still hard to estimate systematic errors.

Assuming that good old cosmology with zero cosmological term is valid and approximating the integral (6) by the expression $t_U \approx [H(1 + \sqrt{\Omega}/2)]^{-1}$ we get

$$\sum_j m_{\nu_j} < 390 \text{ eV} \left(\frac{9.8 \text{ Gyr}}{t_U} - h_{100} \right)^2 \quad (7)$$

With $h_{100} = 0.65$ and $t_U > 12$ Gyr one gets $m_\nu < 10$ eV. With larger H and t_U the bound is even stronger but at some stage the assumption of vanishing Ω_v becomes incompatible with

their high values and one has to invoke nonzero cosmological constant. The bound becomes weaker but still meaningful. For example with $\Omega_{tot} = 1$, $t_U > 14$ Gyr, and $h_{100} > 0.75$ we get $m_\nu < 20$ eV.

There is also the well known bound on the mass of a very heavy neutrino (if it exists) from below[8]: $m_\nu > 3$ GeV. It was obtained with $\Omega_\nu = 0$. Relaxing this assumption one gets the limit 2-3 times weaker. These limits are not very interesting after direct measurement of the decay width of Z^0 made at LEP which showed that there is no space for an extra neutrino with mass below $m_Z/2$. Moreover it is difficult to believe that so heavy neutrinos could be stable on cosmological time scale, though formally it is not excluded.

3 Spectrum of Cosmic Neutrinos

It is assumed usually that cosmic neutrinos (if they are massless) have equilibrium Fermi-Dirac spectrum with vanishing chemical potentials:

$$f_\nu = 1/[\exp(E/T_\nu) + 1] \quad (8)$$

with the temperature $T_\nu = (4/11)^{1/3}T_\gamma = 1.93(T_\gamma/2.7)$. However in contrast to electromagnetic background radiation where spectral distortion is extremely small, below 10^{-4} [9], neutrino spectrum is much more distorted. It is because electrons and neutrinos have different temperatures at $T < m_e$ so that the annihilation $e^+e^- \rightarrow \bar{\nu}\nu$ produces nonequilibrium ν and $\bar{\nu}$ which cannot thermalize at these low temperatures. Calculations of ref.[10] give the result:

$$\delta f_{\nu_e}/f_{\nu_e} \approx 5 \times 10^{-4}(E/T)(11E/4T - 3) \quad (9)$$

Numerical calculations[11] give similar results. The distortion for ν_μ and ν_τ is approximately twice smaller because at that temperatures they have only neutral current interactions.

This effect results in an increase of neutrino number density at the present day by almost 1%. It is not important from the point of view of the bound on their mass. It could be

potentially essential for the primordial nucleosynthesis. Distortion of the electronic neutrino spectrum would change the neutron-to-proton ratio because electronic neutrinos (in contrast to ν_μ and ν_τ) participate in the reactions $n + \nu \leftrightarrow p + e^-$ and $p + \bar{\nu} \leftrightarrow n + e^+$ and directly shift its value (not only through the influence on the cooling rate). If there is an excess of ν_e and equally of $\bar{\nu}_e$ at higher energies (with respect to the equilibrium values) the n/p -ratio would be bigger because the number density of protons is larger than the number density of neutrons by factor $\exp(\Delta m/T)$ and correspondingly destruction of neutrons in the first reaction is less efficient than the production of them in the second reaction. An excess of neutrinos at low energy produces the opposite effect because of threshold 1.8 MeV in the second reaction which inhibits neutron production. The correction (9) could shift the n/p -ratio at per cent level but for this particular case its influence on nucleosynthesis is practically negligible. As we have mentioned above the dependence of n/p -ratio on the spectrum corrections is not sign-definite and it happened that the spectrum was distorted in such a way that n/p -ratio does not change. The effect would be much bigger if nonequilibrium ν_e ($\bar{\nu}_e$) come from the annihilation of heavy tau-neutrinos with the mass around 10 MeV, $\nu_\tau \bar{\nu}_\tau \rightarrow \nu_e \bar{\nu}_e$ [12].

Another possible source of nonequilibrium electronic neutrinos could be decays of massive particles[13, 14] after neutrino decoupling from the cosmic plasma, that takes place around 2 MeV. A possible candidate for the role of the mother-particle is massive ν_τ . As we mentioned above the effect of nonequilibrium ν_e could shift n/p -ratio either way. In particular if n/p goes down, this would relax the Schwartsman bound[15] on the number of massive neutrino species[14] or relax the bound on the baryon-to-photon ratio during nucleosynthesis[16].

4 Bounds on Neutrino Mass from Nucleosynthesis

In the case that neutrinos live longer than nucleosynthesis time, $t_{NS} \sim 100$ sec but shorter than the universe age, $t_U \sim 10^{10}$ years, consideration of primordial nucleosynthesis permits to exclude an interesting interval of ν_τ mass[18, 19], while for ν_e and ν_μ the bounds are

weaker than the experimental ones (1,2). The arguments are essentially the same as those leading to the nucleosynthesis bound on the number of massless neutrino flavors[15]. New particle species in the primeval plasma during nucleosynthesis epoch would change the universe cooling rate and correspondingly the frozen value of neutron-to-proton ratio which predominantly determines abundances of the produced light elements. Concordance with observations leads to the bound on the extra neutrino species, $k_\nu < 1$. Quite recently the bound was more restrictive, $k_\nu < 0.3$ or even $k_\nu < 0.1$ but recent data on primordial ^4He and deuterium created some confusion and the relaxation of the bound. For the details and references see the talk by G. Steigman at this conference[17].

If neutrinos are heavy their influence on the cooling rate would be similar to addition of extra massless neutrino flavors. Though in equilibrium the energy density of massive particles is smaller than that of massless ones, tau-neutrinos with mass in MeV-range went out of equilibrium when their number density is still nonnegligible and since the energy density of nonrelativistic particles in the course of expansion decreases more slowly, they gradually begin to dominate. For example 10 MeV tau neutrino which is stable on the nucleosynthesis time scale is equivalent to almost 7 massless neutrino species if it is a Dirac particles and to 4 species if it is a Majorana one [19]. This argument permits to exclude ν_τ in the mass interval $0.5 < m_{\nu_\tau} < 35$ MeV[18, 19] if the permitted bound on extra neutrino species is $\Delta N_\nu < 0.6$. In the case of a weaker bound, $\delta N_\nu < 1$, the excluded mass interval shrinks to $1 < m_{\nu_\tau} < 30$ MeV. These results are valid for the Majorana type neutrinos. In the Dirac case the lower limits are approximately twice better. It is connected with twice larger number of possible states for the Dirac particles. The occupation number of right-handed neutrinos in the primeval plasma was calculated in ref.[20] (for earlier papers see[21]) where it was shown that in the case of a very strong bound $\Delta N_\nu < 0.1$ the lower end of the excluded interval for the Dirac tau neutrino goes down to approximately 10 KeV.

These results were obtained under assumptions of kinetic equilibrium of neutrinos in the primeval plasma. As is mentioned in the previous section this assumption is violated and

nonequilibrium electronic neutrinos may considerably strengthen the limits. For example nonequilibrium $\nu_e(\bar{\nu}_e)$ coming from the annihilation of 20 MeV tau neutrinos are equivalent to almost one extra neutrino species if ν_τ has the Dirac mass and to 0.15 extra nus if it has the Majorana mass[12].

Tau-neutrinos with MeV mass would not spoil successful nucleosynthesis results if they are unstable on the nucleosynthesis time scale. This case was analyzed in ref.[22]. The bounds on the mass depend upon the life-time and decay channels. For a sufficiently short life-time tau-neutrinos remain in equilibrium during nucleosynthesis, their number density is Boltzmann suppressed and practically any mass is permitted. Another way to avoid the nucleosynthesis bound on the mass is to assume a new interactions for ν_τ which could deplete their density at nucleosynthesis. Since MeV tau-neutrinos should be unstable anyhow a new interaction which generates the decay, is necessary. This could be flavor nonconserving effective four-fermion interaction generating the decay $\nu_\tau \rightarrow 3\nu$ or the Yukawa coupling to a light (or massless) scalar boson (like e.g. Majoron) producing the decay $\nu_\tau \rightarrow J + \nu_l$ where l stands for e or μ . The life-time with respect to these decays may be very long so that ν_τ remains stable during nucleosynthesis. It is possible that the nondiagonal coupling $g'\nu_\tau\nu_l J$ leading to the decay is much weaker than the diagonal one $g\nu_\tau\nu_\tau J$. In this case the annihilation $\nu_\tau + \nu_\tau \rightarrow 2J$ may be efficient during nucleosynthesis diminishing ν_τ number density[23]. This could help to avoid the mass limits mentioned above. For the details and references see also the talk by S.Pastor at this conference.

5 Lepton Asymmetry

It is usually assumed that there is no charge asymmetry in lepton sector, the number density of neutrinos is equal to that of antineutrinos. Lepton asymmetry is not directly observable and in principle may be large. The reason for the assumption of its smallness is a small value of the baryon asymmetry, $(n_B - n_{\bar{B}})/n_\gamma \approx 3 \times 10^{-10}$. Usually theoretical models predict

lepton and baryon asymmetry of about the same magnitude though there may be interesting exceptions. The value of charge asymmetry in kinetic equilibrium can be characterized by chemical potential μ so that the expression (8) is changed to

$$f_\nu = 1/[\exp((E - \mu)/T_\nu) + 1] \quad (10)$$

In chemical equilibrium $\bar{\mu} + \mu = 0$ where $\bar{\mu}$ is the chemical potential of antiparticles. It is convenient to introduce the quantity $\xi = \mu/T$ which remains constant in the course of expansion if the corresponding charge is conserved.

The strongest bound on the magnitude of lepton asymmetry can be derived from primordial nucleosynthesis. Nonzero chemical potential results in an increase of neutrino energy density and in this sense is equivalent to an addition of extra neutrino species. If the nucleosynthesis upper bound is $\Delta n_\nu < 1$ then $|\xi_l| < 1.5$, and if $\Delta n_\nu < 0.3$ then $|\xi_l| < 0.8$. For electronic type neutrinos the limit is much stronger because, as we have mentioned above, the n/p -ratio is especially sensitive to the spectrum of electronic neutrinos. If the data on light element abundances permit one extra neutrino species electronic chemical potential is bounded by $\xi_e < 0.07$. For more details and the list of references see review paper[24].

Lepton asymmetry should be generated along the same lines as the baryon asymmetry, namely by the out-of-equilibrium processes with leptonic charge nonconservation and C and CP breaking[25]. Leptogenesis in GUT models predicts lepton symmetry of the same order as the baryonic one and correspondingly $\xi \leq 10^{-9}$. Electroweak leptogenesis[26] satisfies the condition of $(B - L)$ -conservation and also predicts a very low result for the lepton asymmetry. Moreover if electroweak phase transition is second order then the asymmetry is not generated but washed out by electroweak processes. In this case any preexisting state with arbitrary $B = L$ acquires $B = L = 0$ after electroweak stage. However if there was a primordial lepton asymmetry L_i then after electroweak epoch asymmetry $B = L = L_i/2$ would be generated. The initial lepton asymmetry might come from the out-of-equilibrium decays of heavy Majorana neutrino[27]. One sees that in this case the lepton asymmetry is

very small too. Still there is a hope to generate a large lepton asymmetry in a version[28] of the model of baryogenesis with baryonic (and leptonic) charge condensate[29] (see also [24]). It is essential that electroweak processes would not spoil this result; this could happen if the relevant processes take place below the electroweak scale or if electroweak baryo- and leptogenesis do not operate. The model[28] predicts a relatively small spatial scale of the variation of lepton asymmetry. The concrete size of the scale is model dependent and could quite easily be as small as $O(\text{kpc})$ or as large as $O(\text{Gpc})$. It is interesting if the recently observed[30] different abundances of primordial deuterium at large distances, $z \approx 3$, could be explained by variation of leptonic chemical potentials. If this is the case then not only deuterium but other light elements (especially ${}^4\text{He}$) should have systematically varying abundances.

6 Neutrino Oscillations and New Neutrinos

Neutrino oscillations is probably the central (hypothetical) phenomenon in neutrino physics. There is not yet conclusive laboratory evidence in favor of oscillations but an impressive experimental activity in the field makes one hope for an essential progress in the near future. For the reviews and references see talks by Caldwell[31] and Valle[32] at this conference. There are plenty of indirect evidence in favor of oscillations. First among them is the deficit of solar neutrinos discovered by the group led by Davies whose 80th anniversary we all celebrate here. This deficit may be explained by the resonance neutrino oscillations (the MSW effect) and there is plenty of discussion of the problem at this conference. There are some other observed anomalies in neutrino physics like atmospheric neutrino problem or Karmen anomaly. If all the data are correct the implications could be quite exciting. One possibility is an existence of a new sterile neutrino, ν_s with an efficient oscillations between ν_s and normal neutrinos (for a recent discussion see[33]).

Oscillations into new neutrino states would distort successful nucleosynthesis predictions and hence a bound on oscillations parameters can be derived. Neutrino oscillations in the

hot dense cosmic plasma at high temperatures when neutrinos are strongly coupled to the plasma is a rather complicated phenomenon. It cannot be described by the usual Schroedinger equation but the density matrix formalism should be used instead[34]. At smaller temperatures (roughly speaking below 2-3 MeV), when neutrino scattering dies down, one can return to the Schroedinger equation with the properties of the medium described by refraction index[35]. The bounds on the oscillation parameters derived in refs.[36] are meaningful if primordial nucleosynthesis strongly constraints the number of extra neutrino species. In the case that $\Delta n_\nu = 1$ is permitted no restriction follows from nucleosynthesis for oscillations into one and only one new state. It was argued in ref.[37] that neutrino oscillations could give rise to a large leptonic chemical potentials. This is a very interesting result though it is in contradiction with papers[36]. It deserves further consideration.

Recently there appeared a renewed interest[38, 39, 40, 41] to the old idea of the mirror world[42]. It is assumed that there exists another world almost or exactly symmetrical to ours which is coupled to our world only through gravity and possibly through a new very weak interaction. Such a possibility is inspired by superstrings with the symmetry group $G_{tot} = G \times G'$ (like e.g. $E_8 \times E'_8$). Another world contains the same set of particles and similar interactions. Exact symmetry between the two worlds are forbidden by the nucleosynthesis because the mirror world contributes effectively $\Delta n_\nu = 10.75/1.75 = 6.14$ to the number of massless neutrino species. However if the symmetry is broken so that the (re)heating temperatures after inflation are different the nucleosynthesis constraints may be satisfied. A very interesting phenomenologically model arises if the electroweak symmetry breaking scales are different in our and mirror worlds, $v'/v \approx 30$. To satisfy the nucleosynthesis constraints in this case the ratio of the temperatures of normal and mirror particles at the nucleosynthesis era should be $T'/T < 0.96(\Delta n_\nu)^{1/4}$ [41]. Oscillations between mirror and normal neutrinos with a reasonable choice of parameters may explain all known neutrino anomalies[38]. The model predicts the existence of relatively heavy mirror neutrinos with the mass in keV range which may be warm dark matter while light neutrinos with mass in

eV range are natural candidates for hot dark matter. Because of different electroweak scales the masses of fundamental fermions in the mirror world are about 30 times larger. This results in the absence of stable mirror nuclei and in turn to quite different astrophysics and in particular to an easier black hole formation.

If neutrinos have a magnetic moment then their interaction with magnetic field would result in spin-flip and so normal left-handed neutrinos would be transformed into sterile right-handed ones. If this process was efficient during nucleosynthesis it doubled the number of neutrino species. Assuming that during nucleosynthesis there existed magnetic fields in the primeval plasma which seeded the present-day magnetic fields in galaxies, one can put an upper bound on the neutrino magnetic moment, $\mu_\nu < 10^{-16} \mu_B$ [43] where μ_B is the electron Bohr magneton.

7 Neutrinos and the large Scale Universe Structure

Massive neutrino are natural candidates for dark matter particles. In comparison with other candidates neutrinos have a definite advantage: they are known to exist and it is natural to expect that they are massive. Unfortunately the theory of large scale structure formation with light neutrinos ($m = O(10)\text{eV}$), so called hot dark matter, does not fit the observed picture. Formation of galactic (and smaller) size structures is strongly suppressed. Moreover light neutrinos contradict Tremaine-Gunn limit [44]. Because of Fermi exclusion principle one cannot squeeze arbitrary many neutrinos into a galaxy and to represent invisible mass in dwarf spheroids they should be heavier than 0.3-0.5 keV. So one has to invoke new heavy hypothetical particles (cold dark matter). Cosmology presents one of the strongest arguments in favor of their existence and thus of new physics beyond the standard model. (For the recent review see e.g. ref [45]). Still neutrinos are probably not absolutely useless for structure formation. One of the popular models requests 70% of cold dark matter and 30% of hot dark matter and might be especially good if there are two equal mass neutrinos

with $m = 2.5$ eV[31].

A single component dark matter model looks of course more natural and attractive. Unfortunately with the simple assumption of scale-free (flat) spectrum of initial perturbations[46] such models do not agree with observational data. Addition of 30% of hot dark matter permits to increase the power at large scales without distortion small scales. The same goal can be achieved with heavy (MeV) unstable but long lived particle[47]. A rather natural candidate for such a particle is tau-neutrino. The role of the decaying particle is to enhance the energy density of relativistic matter coming from the product of its decay. This would result in a later onset of nonrelativistic stage and correspondingly to a smaller power of evolved structures at small scales. An improvement of the bound on ν_τ mass is very interesting from the point of view of testing these models.

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